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6.4.2.3 Principal Reactor Types

In ammonia synthesis, the desirable conditions around the reactor system as described above are such that it is normally not possible to go from the inlet to the outlet conditions in the reactor in one adiabatic step. Some type of cooling is required. In principle the cooling can be applied in three different ways:

- internal cooling with cooling tubes in the catalyst bed or with catalyst in tubes surrounded by a cooling medium. The internal cooling can be effected either with gas flow in the same direction in the catalyst bed and cooling channels (cocurrent flow), with gas flow in opposite directions in the catalyst bed and cooling channels (countercurrent flow), or with gas flow in the catalyst bed perpendicular to the flow in cooling channels (cross flow). The cooling medium can be either synthesis gas or some other medium, for example boiling water.
- quench cooling by injection of cold gas. The injection of quench gas can be either between adiabatic beds or into a catalyst bed at different locations. Flow in the catalyst beds can be either axial or radial in vertical converters or downwards in horizontal converters.
- external cooling by heat exchange between catalyst beds. The cooling medium can be either synthesis gas or some other medium, for example boiling water. Flow in the catalyst beds can be either axial or radial in vertical converters or downwards in horizontal converters.

It is of course possible to combine several cooling methods in the same converter system. Furthermore, the catalyst beds and/or heat exchangers including feed effluent heat exchanger may be arranged in one pressure shell or in individual pressure shells. It is clear that this leads to a very significant number of possible converter configurations.

The various converter types may be characterized by the temperature profile through the catalyst bed(s) or by the temperature/concentration profile (plots of temperature vs ammonia concentration for the gas passing the converter) (see Fig. 6.6a–d below). Such profiles are often compared to maximum reaction rate profiles, see Fig. 6.5 (from [460]). It is seen from this figure that when the temperature is increased (at otherwise constant conditions, including constant ammonia concentration), then the reaction rate will increase up to a maximum value; when the temperature is further increased, the rate decreases until it becomes zero at the equilibrium temperature. The temperature/concentration points where maximum rate is achieved describe a curve, the maximum rate curve, which will normally be roughly parallel to the equilibrium curve, but at 30–50 °C lower temperature. It is clear that the minimum catalyst volume would be obtained in a converter where this maximum rate curve were followed. In the early days of ammonia production, available technology limited the obtainable size of the converter pressure shell, and the physical dimensions of the converter

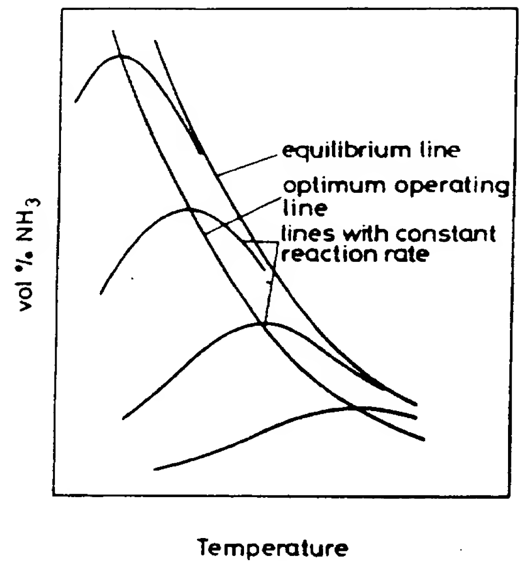


Fig. 6.5. Optimum reaction path or maximum rate curve. The difference between the lines with constant reaction rate is a factor of 10. Lowest reaction rate at highest NH_3 concentration (from [460])

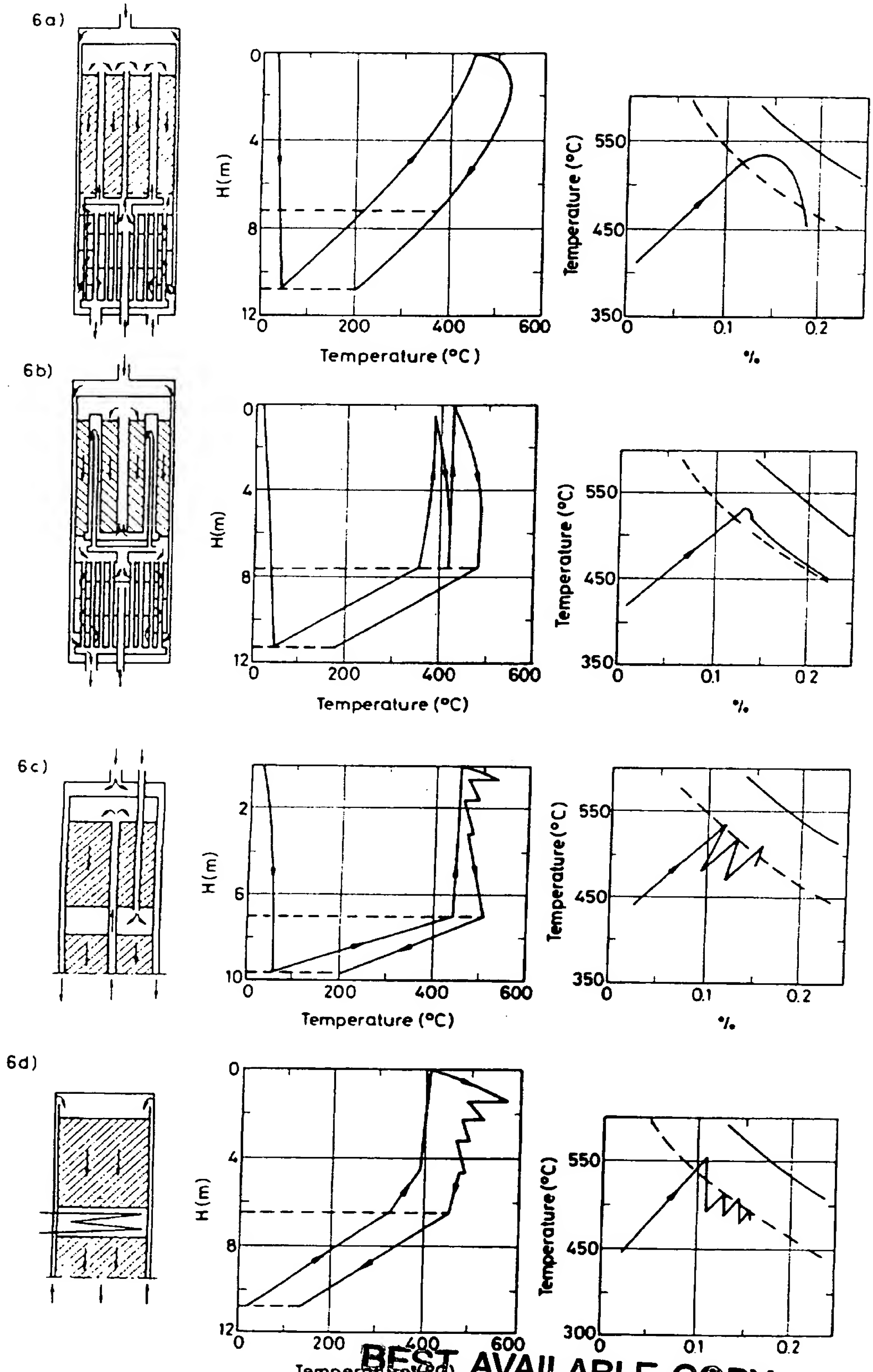
thus limited the achievable production capacity. Great emphasis was therefore given to the ammonia production per unit converter volume. Quite complicated mechanical constructions were used to maximize the production c. pacity of a given volume, and the converters were compared to the "ideal" converter where the temperature/concentration plot follows the maximum rate curve (see e.g. 469)). As technology developed, other considerations such as optimum heat recovery, reliable mechanical construction, easy catalyst loading and unloading, etc. became more important than maximum production per unit volume, and different – mechanically simpler – converter configurations have, therefore, become more popular.

In connection with "revamps", i.e. modification of existing plants for increased capacity and/or increased energy efficiency (see Sect. 6.4.3.4), where the pressure shell of existing converters is reused, it has, however, aga.n become a major consideration to maximize the production capacity of the volume available inside the pressure shell.

Ammonia converters most often consist of two separate parts, an outer pressure vessel and an internal "basket" containing the catalyst bed(s), internal piping for gas distribution, heat exchangers (when applicable) for control of catalyst temperatures, and in some cases a feed-effluent heat exchanger, so that all high temperatures are contained inside the pressure shell.

Early types of ammonia synthesis converters are described in [4, 50, 385]. More recent developments are discussed in [23, 490–492]. Good overall reviews of different converter designs may be found in [493, 494].

A discussion of the types of heaters used for start-up of ammonia synthesis converters (fired vs. electrical heaters) is given in [910].



6a)
6b)
6c)
6d)
H(m)
Temperature (°C)
Temperature (°C)
%

6.4.3 Commercial Ammonia Synthesis Converters

A very significant number of different ammonia synthesis converter designs have been used in industrial practice. In the following survey the different designs have been characterized, first by the cooling principle applied, and thereafter mainly by flow direction through the catalyst bed(s).

6.4.3.1 Converters with Internal Cooling in Catalyst Beds

In converters with internal cooling the required cooling is supplied by a cooling medium which flows in most cases in cooling tubes in the catalyst bed or, in a few designs, around tubes containing the catalyst. The flow in the cooling tubes may be countercurrent or cocurrent (in the opposite direction or the same direction as the flow in the catalyst bed).

6.4.3.1.1 Countercurrent Flow in Cooling Tubes

The most important converter type using internal cooling with countercurrent flow in cooling tubes is ***the TVA-converter***. A schematic drawing of the converter and the corresponding temperature- and temperature/conversion profile is shown in Fig. 6.6a. Feed gas enters at the top and passes in the annulus between the pressure shell and the basket to the bottom of the converter. In this way the pressure vessel is cooled (the feed gas is used as "shell cooling gas") so that a lower design temperature is applicable for the expensive pressure vessel.

The feed gas passes through the feed/effluent heat exchanger, which is contained in the same pressure shell as the catalyst bed (when installed in this position the heat exchanger is often referred to as "the lower heat exchanger"), on the shell side and further up through the cooling tubes in the catalyst bed. After passing in up flow through the cooling tubes the gas turns and flows in down flow through the catalyst bed and further through the tube side of the lower heat exchanger to the exit. A bypass steam (often called "cold shot") is added for temperature control to the feed gas between the lower heat exchanger and the catalyst bed cooling tubes. It is seen from the temperature profile that the gas is at relatively low temperature at converter outlet. This means that the waste heat can be used only for preheating boiler feed water or producing low pressure steam.

Fig. 6.6. Schematic drawing, typical temperature profile, and operating curve (temperature/ammonia concentration plot) for four important converter types. (from [471])
a Internal cooling, countercurrent flow (TVA-converter)
b Internal cooling, cocurrent flow (NEC-converter)
c Quench cooling
d Indirect cooling (heat exchange)

If a design is used where the feed/effluent heat exchanger is located in a separate pressure shell, then the converter outlet temperature becomes equal to the catalyst bed outlet temperature, and the converter outlet system must be designed for this higher temperature. In such systems the waste heat may be recovered at higher temperature so that it can be used, for example, for production of high pressure steam.

The temperature/concentration profile illustrates how the gas reacts almost adiabatically in the first part of the catalyst bed. As the temperature difference between the cooling gas and the reacting gas increases, and the reaction rate decreases due to the approach to equilibrium, the temperature is decreased so that the approach to the equilibrium line increases, and the profile moves close to the maximum reaction rate line. In the bottom of the catalyst bed the reaction rate becomes low, and the temperature drops below the maximum rate line. It is evident that in order to obtain the best performance of this converter type, it is important that the cooling must match the heat evolution. Too efficient cooling will lead to a low reaction rate or even to the loss of reaction, whereas too little cooling will lead to a too close approach to equilibrium and therefore to inefficient use of the catalyst. A TVA-type converter of special design is described in [495]. In this design, core rods are installed in the cooling tubes to enhance heat transfer, thereby reducing the required heat transfer area.

Stability problems and performance optimization of TVA-converters are discussed in [480, 481, 484, 485]. A classical account of operating problems in a synthesis unit using TVA-converters is given in [496] which also gives mechanical details on the construction of a TVA-converter. Drawings showing mechanical details of TVA-converters may also be found in [23, 385, 497, 498]. TVA type converters have been used extensively, and may are in operation today. This converter type has been suggested quite recently for installation in new, relatively small plants (up to about 300 MTPD of ammonia) by process licensors such as Tosøe [499] and ICI [500].

Another converter type using countercurrent flow in cooling tubes is the SBA-converter [501]. In this converter the feed gas enters at the bottom of the pressure shell and passes upwards in the annulus between the pressure shell and the basket, flows down through tubes which serve both as heat exchanger tubes in a gas/gas heat exchanger located in the top of the converter and as cooling tubes in the catalyst bed. The preheated gas passes in up flow through the catalyst bed and through the gas/gas exchanger on the shell side before it leaves the converter at the top. Converters of this type have recently been revamped into Tube Cooled Radial Flow converters [502].

Old converter types with countercurrent flow in cooling tubes are the Mont Cenis reactor [385, 503], the original Haber-Bosch converter [504], the Claude converter [505], and the "old" Fauser converter [506, 507]. These early converter types were all used in relatively small plants; they are not used in modern processes.

Combinations of countercurrent cooled catalyst beds with adiabatic beds have been suggested by ICI [508], Uhde [509] and in [510, 511].

6.4.3.1.2 Cocurrent Flow in Cooling Tubes

The most important converter type using internal cooling with cocurrent flow in cooling tubes in the NEC converter or the Chemico converter. A schematic drawing of the converter and the corresponding temperature and temperature/conversion profile is shown in Fig. 6.6b. Process gas enters the converter at the top, passes downwards in the annulus between the catalyst basket and the pressure shell as shell cooling gas to the shell side of the lower heat exchanger and therefrom to cooling tubes in the catalyst bed. The tubes are bayonet tubes, and the gas flows up through the inner tube, down in the annular space between the two concentric tubes, up through a center pipe and finally down through the catalyst bed and through the tube side of the lower heat exchanger to the exit.

The cocurrent flow makes it possible to obtain a temperature profile which is close to the optimum; the gas is heated adiabatically to a temperature close to the maximum reaction rate curve, and the temperature/conversion profile then follows closely the maximum rate curve for the test of the catalyst bed length.

The NEC- or Chemico converter with cocurrent flow in the cooling tubes has – like the TVA-converter – been used since the early days of the ammonia industry, and many modifications have been suggested. Descriptions of various versions may be found in [23, 385, 492, 512–516]. A converter with cocurrent cooling in flat cooling "fins" in the catalyst bed is described in [517]. A converter type which combines adiabatic catalyst beds with a catalyst bed using cooling tubes with cocurrent flow has been developed by the Japan Consulting Institute [518, 519]. The flow pattern in this converter is as follows: Feed gas enters at the top and passes as shell cooling gas to the bottom of the converter. It passes then on the shell side of a lower heat exchanger and further in an annulus between the tubular cooled catalyst bed and the outer wall of the basket to the top of the tubular cooled bed, in down flow through cooling tubes in the catalyst bed, up through a central pipe to the top of the converter, down through two adiabatic catalyst beds in series with quench cooling between the beds and finally through the tubular cooled catalyst bed and through the tube side of the lower heat exchanger to the exit. Cold gas is added for temperature control after the first passage of the lower heat exchanger and (as quench gas) after the passage of the first adiabatic bed.

6.4.3.1.3 Cross Flow

Ammonia synthesis converters with radial flow in tubular cooled catalyst beds have been suggested by Toyo Engineering Corp. [520] and in [502]. The Toyo concept has, so far, not been used industrially, while the concept described in [502] has, as mentioned above, been demonstrated in revamps of converters originally designed by SBA. It is claimed that the cross flow makes it possible – through proper design of the cooling tube bundles – to optimize the temperature profile so that it follows very closely the maximum reaction rate curve. It is furthermore reported that the heat transfer coefficients obtained in practice in